

Assessment of biomass energy resources and related technologies practice in Bangladesh



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ABSTRACT

Bangladesh is energy starved country facing a severe power crisis for the last few decades because of inadequate power generation capacity compared with demand. The power generation of the country largely depends on the non-renewable (fossil fuel) energy sources, mainly on the natural gas as accounts 64.5% of recent installed capacity. This trend causes rapid depletion of non-renewable energy sources. Thus, it is necessary to trim down the dependency on non-renewable energy sources and utilize the available renewable resources to meet the huge energy demand facing the country. Most of the people living in rural, remote, coastal and isolated areas in Bangladesh have no electricity access yet. However, renewable energy resources, especially biomass can play a pivotal role to electrify those rural, remote, coastal and isolated areas in the country. Humankind has been using biomass as an energy source for thousands of years. This study assesses the bio-energy potential, utilization and related Renewable Energy Technologies (RETs) practice in Bangladesh. Improved cooking stove, biogas plant and biomass briquetting are the major RETs commonly practiced in Bangladesh. The assessment includes the potential of agricultural residue, forest residue, animal manure and municipal solid waste. The estimated total amount of biomass resource available for energy in Bangladesh in 2012–2013 is 90.21 million tons with the annual energy potential of 45.91 million tons of coal equivalent. The recoverable amount of biomass (90.21 million tons) in 2012–2013 has an energy potential of 1344.99 PJ which is equivalent to 373.71 TWh of electricity.

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Contents

1. Introduction.....	445
2. Location and energy status of Bangladesh.....	447
3. Biomass potential in Bangladesh	448
3.1. Agricultural residues	449
3.1.1. Agricultural residue potential and energy recovery.....	450
3.2. Forest residues.....	450
3.2.1. Forest residue potential and energy recovery	451
3.3. Animal manure and human excreta	452
3.3.1. Livestock residue potential and energy recovery	452
3.4. Municipal and industrial solid wastes	453
3.4.1. Municipal solid waste potential and energy recovery.....	453
3.5. Biomass consumption and recoverable potential.....	453
4. Technologies and organizations related to biomass in Bangladesh.....	453
4.1. Improved cooking stoves (ICS)	454
4.2. Biogas plant	455
4.3. Biomass briquetting.....	456

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4.4. Gasification and pyrolysis of organic solid wastes	456
4.5. Municipal solid waste (MSW) composting plant	456
5. Research and development (R&D) activities related to biomass	457
5.1. Infrastructure development company limited (IDCOL)	457
5.2. Grameen shakti (GS)	457
5.3. Bangladesh council of scientific and industrial research (BCSIR)	457
5.4. Bangladesh rural advancement committee (BRAC)	458
5.5. Local government engineering department (LGED)	458
5.6. Rural service foundation (RSF)	458
5.7. Village education resource center (VERC)	458
5.8. GIZ (German agency for international cooperation) Bangladesh	458
5.9. United Nations Development Program (UNDP)	458
6. Concluding remarks	458
Reference	458

1. Introduction

Energy, one of the imperative needs of human being plays a key role for the socio-economic development of developing countries like Bangladesh. Energy consumption pattern of any country indicates the state of socio-economic development. Conventional energy (natural gas, oil, coal) is considered as the main energy source in the world. About 35% of world's primary energy consumption comes from natural gas. Recently, the production of fossil fuels has reached up to 79% compared to other energy sources [1]. Total primary energy consumption in 2012 all over the world was 12476.76 million tons oil equivalent (Mtoe) with an increasing rate of 1.8% over the previous year as shown in Fig. 1 [2]. However, renewable energy source contributes only about 13% of total primary energy consumption. Therefore, emphasis has been given to utilize the renewable energy as to prevent the eminent depletion of indigenous non-renewable energy sources.

Biomass is considered as the prominent source of renewable energy in Bangladesh as well as in the world. In the low income country like Bangladesh, rural households contribute the largest share of the biomass fuel consumption. Biomass energy is a potentially sustainable and relatively environment friendly source of energy. Rapid rate of fossil fuel utilization releases huge amount of CO₂. Currently, over 60% of the greenhouse effect is enhanced by CO₂ [3]. On the other hand, biomass absorbs the same amount of CO₂ in growing that it releases when burned as a fuel. Thus, biomass is carbon dioxide neutral source on sustainable basis utilization [4]. Furthermore, biomass fuels have a minimum contribution to acid rain as they contain negligible amount of sulfur [5]. Therefore, the substitution of fossil fuels for energy production with biomass will result in a net reduction in greenhouse gas emissions [6]. It is expected that biomass energy will be a cost-effective and sustainable option to meet 50% of world energy demands and of reducing carbon emissions from fossil

fuels during the next century [7]. In Bangladesh, most of the rural people along with a large portion of urban people use biomass energy either directly or indirectly to meet the increasing energy demand. Direct consumption involves cooking, space heating and industrial processes. Nevertheless, indirect consumption includes more advanced processes of converting biomass into secondary energy [8]. Recently, traditional consumption of biomass energy decreases rapidly due to the increasing trend of commercial energy consumption and electricity consumption. Rapid urbanization and industrialization accelerates the energy transition from traditional biomass energy consumption to commercial fossil fuels energy consumption and causes a decline in the share of traditional biomass energy consumption [9,10].

Biomass use for power production significantly increased during 2010 in a number of European countries, in the United States, in China, in India and in some other developing countries. Globally, an estimated 83 GW of biomass power capacity was in place by the end of 2012 which was 12% higher than 2011. The global biomass manufacturing market is expected to increase from USD 572.9 billion to USD 693.7 billion during the year 2010–2015. Recently, electricity generation throughout the world from biomass incineration is getting momentum. In 2012, world's total electricity generation from biomass was about 350 TWh with an increasing rate of 5% over the preceding year 2011 as estimated about 335 TWh [11]. Almost 800 biomass power plants with a capacity of more than 8700 MW has started operation over the last 5 years whereas only Europe has more than 1000 active biomass power plants. [12]. In the United States, about 15 GW power was generated in 2012 that accounts almost 18% of world's total bio-power. Germany, the top bio-power producing country in Europe increased its production to 41 TWh in 2012 that was almost 30% of total Europe's electricity generation from biomass as estimated about 136 TWh. Other significant biomass power producers are Sweden, the United Kingdom, Finland, Poland, Italy and the Netherlands. In Asia, Japan's bio-power generation was decreased to 17.2 TWh whereas China's generation was increased to 36 TWh in 2012 [11]. Moreover, India had a total capacity of 3 GW biomass power in year 2010 of which about 0.3 GW was added in that year [12]. Recently, Bangladesh has started to produce electricity from biomass resources.

The study assesses the potentiality of total biomass in Bangladesh from various categories: agricultural residue, forest residue, animal manure and municipal solid waste. It also outlines the potential of electricity generation from the recoverable amount of biomass. However, all the recoverable biomass in Bangladesh is not available for electricity generation as biomass is mainly utilized in the country in traditional pattern. Recently, the country is practicing some RETs includes above 50,000 biogas plants; more than 0.20 million improve stoves and 1000 biomass briquetting

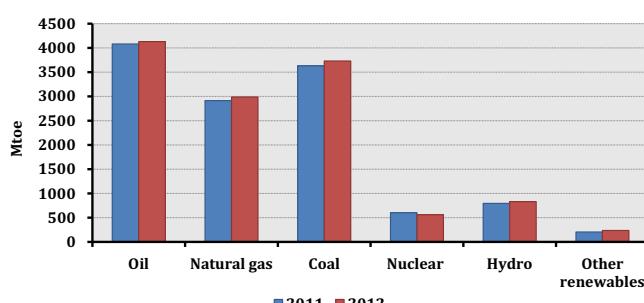


Fig. 1. World's primary energy consumption pattern [2].



Fig. 2. Location, divisions and districts of the People's Republic of Bangladesh [15].

machines to save biomass fuel. Therefore, biomass energy can play an ineluctable role in the sector of rural employment and income.

2. Location and energy status of Bangladesh

Bangladesh, a south Asian country has a location between $20^{\circ} 34'$ and $26^{\circ} 38'$ north latitude and $88^{\circ} 01'$ and $92^{\circ} 41'$ east longitude with an area of 147500 km^2 [13]. In the year 2011, total agricultural land in the country was 91280 km^2 whereas, the arable land and forest area were 76280 km^2 and 14394 km^2 respectively [14]. By the end of 2010, she had a total population of 146 million of which 73.05 million male and 72.95 million female where the present population is about 163.655 million. The country comprises of 7 divisions: Dhaka, Chittagong, Rajshahi, Barisal, Sylhet, Khulna and Rangpur and also 64 districts (Fig. 2) [15]. The country is surrounded by India on the west, north and northeast while Myanmar on the south-east and the Bay of Bengal on the south and forms a deltaic plain land comprises of three major rivers: the Ganges, the Brahmaputra and the Meghna along with a network of numerous rivers, canals, haors, baors and beels. The low, flat and fertile lands of the country except the hilly regions in the northeast, some high lands in the north and north-western part are mainly used for cultivation and settlement. Agriculture is the major occupation for over 60% of the population due to fertile land. Moreover, Bangladesh enjoys generally a sub-tropical monsoon climate and the climate follows a four-season cycle: winter (December–February), summer (March–May), monsoon (June–September) and autumn (October–November).

Bangladesh is facing daunting energy crisis with the lowest per capita energy consumption in the world. In the year 2011, the country had per capita energy consumption of 205 kg oil equivalent (kgoe) was low compared to 614 kgoe for India, 482 kgoe for Pakistan, 499 kgoe for Sri Lanka, 383 kgoe for Nepal and far below the world per capita of 1890 kgoe [16]. Total primary energy consumption of the country including modern renewables used to generate electricity in 2012 was about 26.3 Mtoe almost 7.5% higher than previous year as estimated about 24.4 Mtoe. The primary energy consumption pattern of Bangladesh in 2012 is shown in Fig. 3 [2]. Recently, the biomass energy consumption in Bangladesh is reached around 70% of total energy consumption. However, most of them are used in traditional purposes like cooking and heating. Thus, electricity generation from biomass in Bangladesh is still very low ($< 0.05 \text{ Mtoe}$).

In Bangladesh, the electricity generation is natural gas dependent and it contributes about 6587 MW of total installed capacity 10213 MW on November, 2013 as shown in Fig. 4 [17]. Over 85%

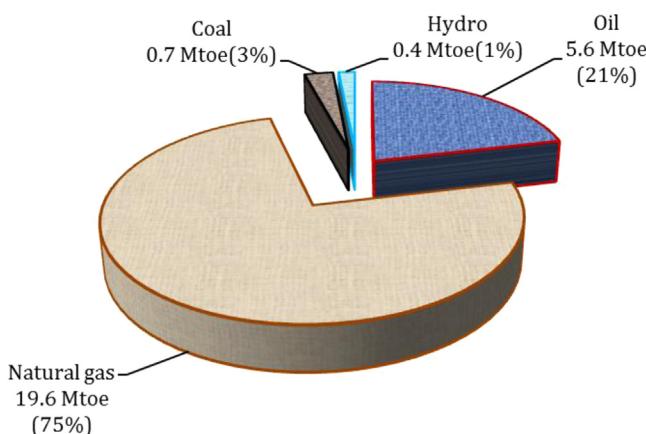


Fig. 3. Primary energy consumption pattern in Bangladesh [2].

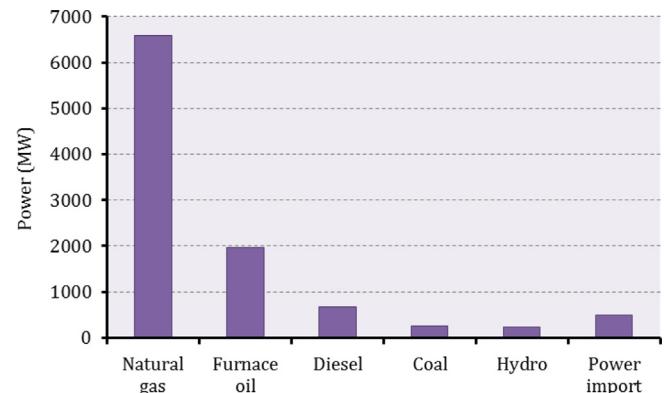


Fig. 4. Installed capacity of electricity generation scenario by fuel type [17].

Table 1
Power crisis in Bangladesh [17,18].

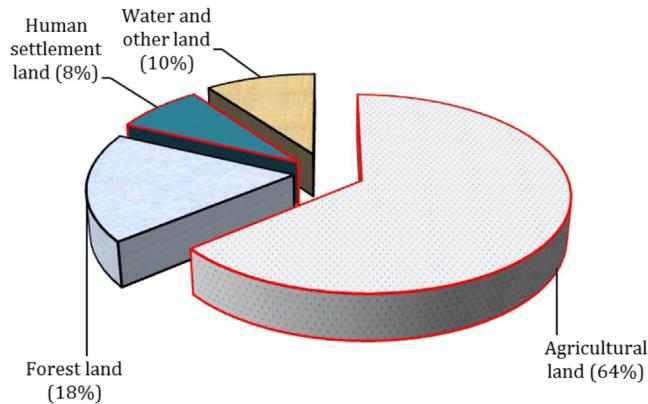
Fiscal year	Installed capacity (MW)	Maximum generation (MW)	Maximum demand (MW)	Load shedding (MW)
2005–2006	4690	3810	4490	1312
2006–2007	4693	3849	4550	1212
2007–2008	5466	4415	4800	385
2008–2009	5803	4162	5200	1269
2009–2010	5978	4606	5800	1350
2010–2011	6727	4890	6500	1100
2011–2012	8100	6066	7518	1058
2012–2013	8525	6350	8349	1000

people lives in rural, coastal, remote and isolated areas in Bangladesh and only few of them has electricity access. In overall, only about 49% of total population has access to electricity which is lower than the other countries of the world. In the country, electricity generation is inadequate to meet the increasing demand because of natural gas dependent generation style and poor infrastructure. The increasing demand scenario of gas is based on the projected requirement of urban based power plants, fertilizer factories, industrial and commercial units to be built in future. This projection does not envisage providing natural gas directly to the vast majority of the rural people because of limited gas pipe line infrastructure to connect thousands of villages throughout the country and inability of rural population to purchase the pipe line gas in their households. However, this situation forces the rural population to rely on the traditional biomass sources for their household energy supply. This is however not only a case with Bangladesh, but many other developing nations like India, Pakistan, Nepal, Sri Lanka, Thailand, China etc. Recent diminishing pattern of the indigenous fossil fuel causes environment pollution. Currently, consumers cannot be provided with uninterrupted and quality supply of electricity due to this inadequate generation compared to the national demand and the country is facing a large unsatisfied energy demand. Moreover, industrial production and household life are regularly hampered due to regular load shedding problem which is hampering our economy as well as making us lag behind. A recent survey shows that the maximum electricity generation is 6350 MW whereas, the maximum demand is 8349 MW causes 1000 MW load shedding during the fiscal year 2012–2013 as shown in Table 1 [17,18]. It is unfortunate that as a nation we have not been able to resolve this problem even after 40 years of our independence. Sufficient energy supply to the people is government's constitutional responsibility. For this, government of Bangladesh has made vision and policy statement regarding power

Table 2

Utilization pattern of biomass in Bangladesh.

Primary source	Residue	Utilization
Agricultural crops		
Rice	Rice straw Rice husk	(i) Animal feed, (ii) animal bedding, (iii) housing materials, and (iv) fuel (i) Poultry bedding, (ii) cattle feed, and (iii) Fuel
Wheat	Wheat straw	(i) Fuel and (ii) housing material
Jute	Jute stalk	(i) Fuel and (ii) housing material
Groundnut	Groundnut straw	(i) Fuel and (ii) animal feed
Vegetable	Vegetable plants	(i) Fuel and (ii) animal feed
Pulse	Pulse straw	(i) Fuel and (ii) animal feed
Sugarcane	Sugarcane leaves Sugarcane bagasse	(i) Fuel and (ii) animal feed (i) Fuel
Maize	Maize leaf and straw Maize husk	(i) Fuel and (ii) animal feed (i) Fuel
Forrest	Leaves, twigs and branches Wood	(i) Fuel and (ii) fencing (i) Furniture and (ii) fuel (i) Fuel
Animal waste	Wood residue Cow dung Poultry excreta Goat feces Buffalo dung Cattle bedding material	(i) Manure and (ii) fuel (i) Manure (i) Manure (i) Manure and (ii) fuel (i) Compost
Solid waste	Industrial waste Kitchen waste	(i) Recycling and (ii) fuel (i) Manure and (ii) animal feed

**Fig. 5.** Land utilization pattern in Bangladesh [20].**Table 3**Annual agricultural crops production scenario in Bangladesh (10^5 t) [13,21–27].

Crops	2006–2007	2007–2008	2008–2009	2009–2010	2010–2011	2012–2013
Rice	265.53	289.31	313.17	322.57	335.42	344.30
Wheat	7.35	8.44	8.44	9.69	9.72	10.36
Maize	5.22	13.46	7.30	8.87	10.18	20.42
Sugarcane	55.11	49.84	52.33	44.91	46.71	73.00
Jute	8.38	8.39	–	9.24	18.48	16.57
Pulse	2.79	2.04	1.96	2.18	2.31	7.67
Coconut	3.25	3.34	3.16	4.02	3.26	3.26
Millet	0.25	0.23	0.24	0.24	–	0.24
Groundnut	0.38	0.44	0.47	0.53	0.54	1.26
Vegetable	59.52	86.85	106.22	108.69	111.94	132.21
Cotton	0.15	0.08	0.09	0.11	0.16	0.28
Tea	0.580	0.590	0.590	0.600	0.61	0.55
Tobacco	0.43	0.4	0.4	0.5 4	0.79	0.79
Barley	0.01	0.001	0.001	0.001	0.005	0.007
Total	408.95	463.42	461.89	504.7	540.125	610.917

sector improvement to ensure the access of reliable electricity to the majority of the people of Bangladesh by 2020.

However, lack of capital investment is the major stumbling block for energy development programs. Some government organization (GO) and non-government organizations (NGOs) have

Table 4
Agricultural residue production ratio (RPR).

Crop residues	Residues production ratio (RPR)	
	Value	Reference
Field residues		
Rice straws	0.10, 0.447, 1.0, 1.757	[28,29,4,30]
Wheat straws	0.50, 1.75, 1.48, 1.70, 1.5	[31,30,32,33,34]
Maize stalks	2.0, 2.08, 1.0, 2.0	[31,32,35,36]
Sugarcane leaves	0.1, 0.30	[36,37]
Jute stalks	2.0, 1.37, 2.0	[38,34,32]
Millet stalks	1.75, 1.10, 1.50	[30,39,33]
Groundnut straws	2.26, 2.3	[40,41]
Cotton stalks	3.232, 3.52	[29,40]
Barley straws	1.75, 1.58, 1.7	[30,32,33]
Process residues		
Rice husk	0.23, 0.23, 0.20	[28,42,4]
Maize cob	0.25, 0.273, 0.30, 0.30	[42,30,36,43]
Maize husks	0.20, 0.20, 0.30	[38,44,43]
Sugarcane bagasse	0.33, 0.25, 0.29, 0.289	[28,29,30,45]
Groundnut husks	0.477, 0.50, 0.50, 1.20	[30,38,40,44]
Coconut shells	0.15, 0.16, 0.12, 0.65, 0.438	[28,46,30,38,45]
Coconut husks	0.33, 0.362, 0.419, 1.6	[28,46,30,38]

started to use renewable energy potential for improving cooking and heating efficiency and also to generate electricity through some RETs like biogas plant, improved cooker, biomass briquetting machine, and solar home system etc. Although the government has taken several initiatives for reducing the crisis of electricity, yet the crisis persists. Therefore, attention has drawn to utilize the available indigenous renewable energy source to minimize this power crisis.

3. Biomass potential in Bangladesh

Biomass energy is the only one that has both the property of fossil fuel and characteristics which mean that it can be stored, renewed and transferred. In Bangladesh, biomass is the major renewable energy source mainly used for rural cooking and heating purposes. In India, biomass fuels consumption in rural areas is about 80% of total energy consumption and fuel wood is most dominant accounting for 54% of biofuels [19]. Bangladesh is

endowed with enormous amount of biomass resources due to its extensive non-commercial use. In addition, the rain fed ecosystem produces huge amounts of biomass resources. Biomass is preferred as a clean energy that comprises: agricultural residue, forest residue, animal manure and municipal solid waste. In the country, biomass is commonly used as fuel mostly in the rural areas. The utilization pattern of the most common biomass sources in Bangladesh is shown in Table 2. Firewood, cow dung, leaves and twigs, branches, rice straw and rice husk are used as the biomass fuels mainly for the cooking purpose in rural areas of Bangladesh.

The biomass energy resources are beneficial for many advantages such as vaster resource capacity, lower price, less sulfur composition, less ash content and the feature of renewability. On the other hand, it has also some unfavorable aspects such as higher water content, lower unit thermal output, large volume, decentralized resource and unsuitable for collection, storage and transportation. However, a combination between suitable measure of potentiality, local conditions, use of available science and technology, selection of a reasonable technical program, adoption of advanced techniques, development of new energy conversion methods, attention to the energy utilization efficiency and economy of biological system can cause the biomass resources more efficient and effective for the country to meet the future energy demand.

Table 5
Total agricultural residue recovery on wet basis.

Crop residues	Residue production ratio (RPR)		Residues generation (10 ³ t)	Residues recovery (10 ³ t)
	Value	Reference		
Field residues				
Rice straws	1.695	[50]	58358.35	20425.60
Wheat straws	1.75	[51]	1813	634.55
Maize stalks	2	[51]	4084	1429.40
Sugarcane leafs	0.3	[51]	2190	766.50
Jute stalks	3	[51]	4971	1739.85
Pulses residue ^a	1.9	[52]	1457.30	510.06
Millet stalks	1.75	[51]	42	14.70
Groundnut straws	2.3	[51]	289.80	101.43
Vegetables residue ^a	0.4	[52]	5288.40	1850.94
Cotton stalks	2.755	[51]	77.14	27
Tobacco stalks ^b	2.0	–	158	55.30
Barley straws	1.75	[30]	1.23	0.43
Total field based			78730.22	27555.76
Process residues				
Rice husk	0.267	[50]	9192.81	9192.81
Rice bran	0.083	[50]	2857.69	2857.69
Maize cob	0.273	[51]	557.47	557.47
Maize husks	0.2	[51]	408.40	408.40
Sugarcane bagasse	0.29	[51]	2117	2117
Groundnut husks	0.477	[51]	60.10	60.10
Coconut shells	0.12	[51]	39.12	39.12
Coconut husks	0.41	[51]	133.66	133.66
Total process based			15366.25	15366.25
Total			94096.47	42922.01

^a All the residues are considered as field residue.

^b For Tobacco stalks RPR is considered as 2.00.

3.1. Agricultural residues

Bangladesh is an agriculture based country where more than 60% of the people live in rural areas. The economy of Bangladesh depends principally on agriculture and around 65% of our economic activities are based on agriculture. In Bangladesh about 64% of total land is used for agriculture as shown in Fig. 5 [20]. The main crops produced are rice, sugarcane, vegetables, wheat, jute, pulses, coconut, maize, millet, cotton and groundnut. In 1991–1992 total food grains production in Bangladesh was 19.32 million tons which has gradually increased to 29.77 million tons in 2007–2008. In 2012–2013 total food grain production has reached to 35.10 million tons of which only rice production was 34.43 million tons. Table 3 shows the agricultural crops production scenario in Bangladesh [13,21–27]. Amount of residue production depends on the agricultural crops production.

Agricultural crops generate large quantities of residues which represent an important source of energy both for domestic as well as industrial purposes. Agricultural residues represent the major portion of the total recoverable biomass. Typically, agricultural residues vastly meet the household energy demands in rural and

Table 6
Energy potential of agricultural residue.

Crop residues	Moisture content		Dry residues recovery (10 ³ t)	Lower calorific value (GJ/ton)	Energy content (PJ)
	%	Reference			
Field residues					
Rice straws	12.7	[50]	17831.55	16.30	[50]
Wheat straws	7.5	[52]	586.96	15.76	[52]
Maize stalks	12	[52]	1257.87	14.70	[52]
Sugarcane leafs	50	[53]	383.25	15.81	[51]
Jute stalks	9.5	[52]	1574.56	16.91	[52]
Pulses residue	20	[52]	408.05	12.80	[52]
Millet stalks	15	[30]	12.51	12.38	[51]
Groundnut straws	12.1	[53]	89.16	17.58	[53]
Vegetables residue	20	[52]	1480.75	13.00	[52]
Cotton stalks	12	[52]	23.76	16.40	[52]
Tobacco stalks	8.9	[54]	50.38	17.70	[54]
Barley straws	15	[30]	0.37	12.38	[30]
Total field based	–	–	23699.17	–	–
Process residues					
Rice husk	12.4	[50]	8052.90	16.30	[50]
Rice bran	9	[52]	2600.50	13.97	[51]
Maize cob	15	[52]	473.85	14.00	[52]
Maize husks	11.1	[53]	363.07	17.27	[52]
Sugarcane bagasse	49	[50]	1079.67	18.10	[51]
Groundnut husks	8.2	[53]	55.17	15.66	[53]
Coconut shells	8	[52]	35.99	18.53	[51]
Coconut husks	11	[52]	118.96	18.53	[51]
Total process based	–	–	12780.11	–	–
Total	–	–	36479.28	–	–
					582.33

Table 7
Type of forest in Bangladesh [55].

Forest type	District
Mangrove forest (tropical evergreen)	
Sundarbans	Kulna and Satkhira
Coastal	Cox's Bazaar, Chittagong, Noakhali, Barishal, Patuakhali and adjacent coastal district
Hill forest (tropical moist evergreen)	Chittagong, Sylhet, Comilla, Rangamati, Bandarban and Khagrachari
Plain land sal forest (tropical moist deciduous)	Dhaka, Tangail, Mymensingh, Dinajpur

Table 8
Wood fuel consumption pattern of some countries [56].

Country	Forest area (1000 ha)	GDP per capita (USD)	Total wood fuel production (1000 m ³)	Wood fuel consumption (m ³ /year)	
				Total (1000)	Per capita
Low economies countries (GDP per capita \leq 905 USD)					
Nepal	3636	273	12692	12692	0.47
Bangladesh	871	392	27662	27662	0.18
Cambodia	10447	444	9221	9221	0.66
Lao PDR	16142	509	5944	5944	1.05
Vietnam	12931	622	26350	26350	0.31
Pakistan	1902	704	26500	25899	0.16
India	67701	710	305485	305485	0.27
Mongolia	10252	812	186	621	0.24
Papua New Guinea	29437	815	5533	754	0.12
Middle economies countries (GDP per capita 906–11115 USD)					
Philippines	7162	1163	12950	12950	0.15
Sri Lanka	1933	1231	5584	5584	0.29
Indonesia	88495	1269	73720	82194	0.36
Bhutan	3195	1299	4546	4546	7.14
China	197290	1709	191042	207251	0.16
Maldives	1	2560	0	14	0.05
Thailand	14520	2797	19866	19866	0.32
Malaysia	20890	5098	3068	3068	0.12
High Economies Countries (GDP per capita \geq 11116 USD)					
Korea, Rep.	6265	16533	2465	2465	0.05
New Zealand	8309	26675	0	542	0.13
Singapore	2	26966	0	35	0.01
Japan	24868	35450	110	1234	0.01
Australia	163678	36079	5601	8445	0.42

Table 9
Forest residues production scenario in Bangladesh.

Wood products	Amount (1000 m ³)	Amount (million tons)	Reference
Wood fuel including wood for charcoal	27128	15.459	[58]
Tree residues	–	1.821	[55]
Wood processing residue			
Saw log and veneer log	174	0.099	[58]
Plywood and industrial round wood split	91	0.052	[58]
Pulpwood, round, split and Particle board	20	0.011	[58]
Subtotal	285	0.162	–
Total	27572	17.442	–

semi-urban areas. Residue production from crops is based on the residue production rate (RPR). A numerous researches have been conducted in neighboring Asian countries to produce useful

residue to yield ratio for several agricultural crops as shown in Table 4.

Crop residues include two types of residue such as field residue and process residue. Field residues are left in the field after harvesting and are generally used as fertilizer [47]. Not all field residues are recoverable. The specific local climatic and soil conditions affect the percentage of field residues of a crop to be recycled onto the land [48]. Process residues are generated during crop processing, e.g., milling. These residues are available at a central location [49]. It has been considered that only 35% of field crop residues can be removed without adverse effects on the future yields [48]. On the other hand, crop processing residues have a 100% recovery factor [7].

3.1.1. Agricultural residue potential and energy recovery

The agricultural residue potential depends on the amount of crops and agricultural lands. The availability measurement of residues from field and crop processing area is very difficult because of unavailability of actual residue generation data. Thus, the amount of residue generation is estimated on the basis of residue production ratio (RPR). For each crop, a residual factor determines the ratio between the amount of the crop residue and the main product or crop yield. The amount of recovered residue was estimated on wet basis considering the residue recovery factor as shown in Table 5. Accordingly, in 2012–2013 it is estimated that the total annual amount of recoverable agricultural-crop residues (wet) in Bangladesh was about 42.92 million tons, of which 64.2% are field residues and 35.8% process residues.

Considering the moisture content of each crop, dry amount of crops residues are estimated. Total net recovery of residue was 36.48 million tons comprises of 64.97% field based residue and 35.03% process residue. Total amount of energy that can be recovered from the agricultural residues estimated as 582.33 PJ includes 378.57 PJ from field residue and 203.76 PJ from process residue as shown in Table 6.

3.2. Forest residues

Forest plays a vital role to maintain a balance eco-system. Furthermore, significant amount of rural energy consumption in Bangladesh is met by forest wood and residues. Bangladesh has a petty amount of forest land account as 2.6 million hectares (18%) of total land area 14.8 million hectares [20]. However, the forest land is waning due to deforestation because of urbanization and cultivation. Table 7 shows the distribution pattern of forest in Bangladesh [55]. Forest biomass encompasses wood fuel, tree residues (twigs, leaves, bark and roots) and wood processing residues (saw dust, plywood dust, veneer log dust etc.). Wood has been well-thought-out as a convenient and renewable fuel since humans first used fire for cooking and heating.

Fuel wood is a prevailing one among the forest derived biomass continues to play a momentous role as energy resources in both rural and urban areas in Bangladesh. Fuel wood consumption rate is 0.0654 m³ per head where the timber consumption rate is

0.01076 m³ per head in Bangladesh are very low compared to other developing countries [20]. The homesteads trees are the major sources of wood fuel in rural households consist of firewood, twigs and leaves [49]. Nevertheless, trees are used as timber in urban, semi-urban areas and industries. Recently, Bangladesh has an acute shortage of wood fuel. However, effectual use of forest residues could be a renewable source of energy in the country. The total world wood fuel consumption in 2005 was about 1.9 billion m³ and the Asia-Pacific region shares 787 million m³ (41%) of the world total consumption. Total fuel wood production in Bangladesh in 2005 was 27.66 million m³ as per

capita consumption rate was 0.18 m³ [56]. Table 8 shows the wood fuel consumption scenario of some countries in the world in 2005 [56].

3.2.1. Forest residue potential and energy recovery

Forest residues are commonly left on the forest floor after wood harvest. Wood residues are residues that are obtained from logging and wood-processing such as saw-milling and manufacturing of plywood and particle board. Most of the wood is removed as firewood for domestic consumption. However,

Table 10
Energy potential of forest residues in Bangladesh.

Forest products	Amount (million tons)	Moisture content		Net amount (million tons)	Lower calorific value		Energy content (PJ)
		%	Reference		GJ/ton	Reference	
Wood fuel	15.459	20	[50]	12.3672	15.00	[7]	185.51
Tree residues ^a	1.821	–	–	1.821	12.52	[55]	22.80
Wood residue	0.162	20	[50]	0.1296	18.00	[7]	2.33
Total	17.442	–	–	14.3178	–	–	210.64

^a Tree residue is considered as 100% dry.

Table 11
Livestock in millions head in Bangladesh [59].

Animals	2007–2008	2008–2009	2009–2010	2010–2011	2011–2012	2012–2013
Cattle	22.9	22.976	23.031	23.121	23.195	23.241
Goat	21.56	22.401	23.275	24.149	25.116	25.212
Sheep	2.78	2.877	2.977	3.002	3.082	3.120
Buffalo	1.26	1.304	1.349	1.394	1.443	1.447
Total animals	48.5	49.558	50.632	51.666	52.836	53.020
Chicken	212.47	221.394	228.035	234.686	242.866	246.60
Duck	39.84	41.234	42.677	44.120	45.700	46.635
Total poultry	252.31	262.628	270.712	278.806	288.566	293.235

Table 12
Residue generation from livestock.

livestock	Heads (millions)	Dung yield (kg/animal/day)	Reference	Residues generation (tons/year)
Cattle	23.241	5–10	[49]	63622237.5
Goat	25.212	0.25–0.5	[49]	3450892.5
Sheep	3.120	0.25–0.5	[49]	427050
Buffalo	1.447	8–12	[49]	5281550
Pig	0.101	0.8	[62]	29492
Total animal	53.121	–	–	72811222
Chicken	246.60	0.1	[49]	9000900
Duck	46.635	0.1	[49]	1702177.5
Total poultry	293.235	–	–	10703077.5
Human	163.655	0.09	[61]	5376066.75
Total	510.011	–	–	88890366.25

Table 13
Energy potential of livestock residues.

livestock	Residues recovery (tons/year)	Moisture content		Dry residues recovery (tons/year)	Lower calorific value		Energy content (PJ)
		%	Reference		GJ/ton	Reference	
Animal	43686733.2	40	[47]	26212039.92	13.86	[64]	363.30
Poultry	5351538.75	50	[47]	2675769.375	13.50	[63]	36.12
Human ^a	5376066.75	–	–	5376066.75	10.60	[7]	56.99
Total	54414338.7	–	–	34263876.05	–	–	456.41

^a Calculation of human waste generation rate is based on dry matter.

recovery rates vary with local practices as well as species [57]. Wood processing residues and recycled wood are important sources of energy where plywood mills and sawmills produce same amount of residues [51]. In the year 2011 production of wood fuel including charcoal was 27.128 million m³ as shown in Table 9 [58]. Moreover, 0.285 million m³ wood residues include saw log and veneer log, plywood, pulpwood and particle board dust was produced in 2011. In 1992 tree residue was estimated about 1.821 million tons [55]. However, these data were used for calculation of energy potential due to unavailable data of wood fuel, tree residue and wood processing residues in 2012–2013. Considering the mass density of 0.57 t/m³, total forest biomass was estimated about 17.44 million tons in 2012–2013. The recovery rate of forest derived biomass was considered as 100% [7]. Accordingly, the recoverable amount of biomass from forest and forest industry in Bangladesh in 2012–2013 was estimated about 17.44 million tons.

Not all the residues are considered as dry rather than tree residues. Wood fuel and wood processing residues have moisture content of 20% [50]. Therefore, total recoverable dry residues in 2012–2013 estimated about 14.32 million tons where in 2003 the amount was 7.461 million tons [7]. Considering the lower calorific value of each residue, total recoverable energy potential was estimated about 210.64 PJ in year 2012–2013 as shown in Table 10 which was 107.684 PJ in 2003 [7] and increased by 10.62% per year on average.

3.3. Animal manure and human excreta

Bangladesh has a massive number of livestock potential. In this study livestock includes cattle, buffalo, sheep, goat etc. Animal manure i.e. cow dung, sheep and goat waste are traditionally used as cooking fuel and fertilizer in rural areas of Bangladesh. Besides, most of the poultry droppings in the country are used as fertilizer. In the fiscal year 2004–2005 the country had 44.41 million animals raised to 53.02 million in 2012–2013 wherein cattle and goat were dominant as shown in Table 11 [59]. It has been reported among the working cattle 92% is used for cultivation and 0.19% is for transportation [60]. Moreover, total number of poultry estimated in 2012–2013 in the country was 293.235 million contains 246.60 million chickens and 46.635 million ducks [59]. On the other hand, 163.655 million human beings in the country produce a vast amount of excreta. Therefore, total livestock is estimated about 510.011 million head.

3.3.1. Livestock residue potential and energy recovery

Manure generation from livestock varies from region to region. Besides, waste generations are influenced by body size, type of feed and level of nutrition of the livestock [47]. Dung yield was estimated as 8–12 kg/animal/day for buffalo, 5–10 kg/animal/day for cattle, 0.25–0.50 kg/animal/day for sheep and goat [49]. The feces generation rate for both chickens and ducks was considered as 0.1 kg/animal/day. Waste generation from human was taken as 0.09 kg/human/day based on dry matter [61].

However, annual waste generation was estimated by taking the average of the lower and higher dung yield. Accordingly, total wet residue from livestock in year 2012–2013 was estimated about 88.89 million tons as shown in Table 12. The recovery rate of poultry droppings and animal waste has been considered about 50% and 60% respectively [61,63]. On the contrary, 100% recovery rate has been considered for human excreta [7]. Considering the moisture content of animal waste and poultry droppings to be 40% and 50% respectively [47], total dry residues recovery in 2012–2013 estimated about 34.26 million tons equivalent to 456.41 PJ as shown in Table 13. Nonetheless, estimated residues recovery in 2003 was 25.156 million tons equivalent to 337.67 PJ [7].

Table 14
MSW generation in Bangladesh.

Solid waste	Waste generation		
	kg/capita/day	Reference	million ton/year
Urban	0.41	[68]	6.96
Rural	0.15	[7]	6.42
Total	–	–	13.38

Table 15
Energy potential of MSW in Bangladesh.

Solid waste	Waste recovery (million ton/year)	Moisture content %	Dry recovered waste (million ton/year)	Lower calorific value GJ/ton		Energy content (PJ)
				Reference	Reference	
Urban	4.872	45 [7]	2.6796	18.56 [7]	49.73	
Rural	4.494	45 [7]	2.4717	18.56 [7]	45.88	
Total	9.366	– –	5.1513	– –	95.61	

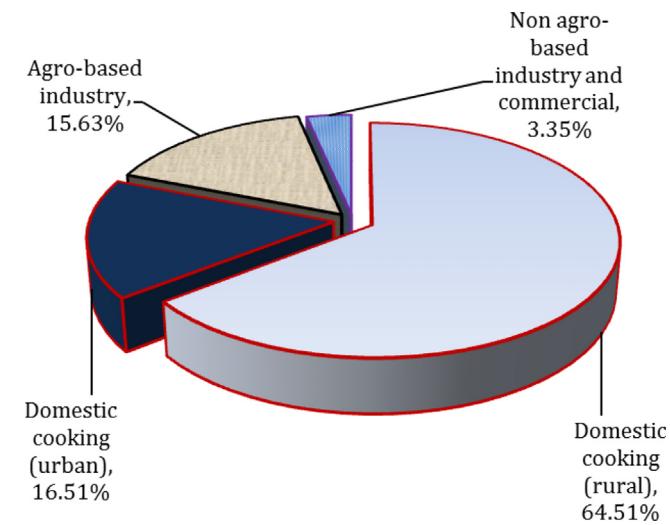


Fig. 6. Biomass consumption for energy in Bangladesh [71].

Table 16
People relying on biomass resources as their primary fuel for cooking [11].

Country	Population		
	Millions	% of country	% of world
Africa	698	68	26.97
Nigeria	117	74	4.52
Ethiopia	82	96	3.17
Democratic Republic of the Congo	63	93	2.43
Tanzania	42	94	1.62
Kenya	33	80	1.28
Other Sub-Saharan Africa	328	75	12.67
North Africa	2	1	0.08
Developing Asia	1814	51	70.09
India	772	66	29.83
Bangladesh	149	91	5.76
Indonesia	128	55	4.95
Pakistan	111	64	4.29
Philippines	47	50	1.82
Vietnam	49	56	1.89
Rest of developing Asia	171	54	6.61
Latin America	65	14	2.51
Middle East	10	5	0.39
World	2588	38	100

3.4. Municipal and industrial solid wastes

Municipal solid waste (MSW) is a severe environmental threat and social problem facing the country. At present, the country has 522 urban centers including 311 municipalities and 9 city corporations. Recently, an enormous volume of solid waste is generated every day in the municipal areas in the country due to rapid urbanization and population growth. The major sources of waste are households, commercial areas, industries and hospitals. The solid wastes include organic matter, paper, plastic, textile and wood, leather and rubber, metal, glass etc. However, in most of the city corporations and municipalities there is no separate solid waste management department as it is not well organized till now and tactlessly solid waste management is being worsened day by day. Landfill is the most common practice in Bangladesh for waste disposal which has a negative impact on environment. The country has a few resource recovery plants [65], although there is a great opportunity of producing energy like gas as well as electricity. Most of the developed countries in the world generate electricity from solid wastes via incineration or gasification or through landfill methane capture and has focused on waste-to-energy (WTE) solutions [66]. On the other hand, thermal treatment may reduce the waste volume up to 90%; this simultaneously could address two problems: disposal of solid waste and generation of electricity [67]. Currently, some initiatives have been taken to utilize this massive amount of waste generated in the country. The effective use (energy utilization or electricity generation) of this gigantic amount of MSW will reduce the adverse effects on environment as well as meet the increasing electricity demand of the country.

3.4.1. Municipal solid waste potential and energy recovery

It has been considered that the waste generation rate in urban and rural areas in Bangladesh is 0.41 kg/capita/day [68] and 0.15 kg/capita/day [7]. The urban MSW generation rate in Bangladesh is comparable to an average per capita MSW generation rate of 0.3 and 0.57 kg/capita/day in two Indian large cities namely Kanpur and Calcutta respectively [69]. In year 2013, the urban and the rural population were reported as 46.47802 million and 117.17698 million respectively in Bangladesh. Therefore, total MSW generation in the country was calculated by multiplying the total population to respective generation rate and estimated to be 13.38 million tons in 2013 as shown in Table 14. It has been estimated that the recovery rate of MSW is 70% [70]. Another study showed 100% recovery rate [7]. Thus, considering 70% recovery rate the estimated recoverable amount in 2013 was 9.366 million tons as shown in Table 15. Total energy potential in 2013 was calculated about 95.61 PJ by taking the moisture content and lower calorific value as 45% and 18.56 GJ/ton respectively [7].

3.5. Biomass consumption and recoverable potential

Traditionally, biomass is generated from rural areas and used for domestic cooking and heating. Furthermore, it is used in urban

areas as well as some industries for process heating. Over 80% of biomass is consumed for domestic cooking as shown in Fig. 6 [71]. In the early 80s biomass dominated energy requirement of the country. Table 16 shows the biomass dependency of some countries in the world for cooking in 2012 [11]. The biomass consumption pattern depends on socio-economic condition and availability of commercial energy and varies region to region [72,73]. Agricultural biomass is commonly used for cooking, heating, fertilizer, animal feeding, bedding etc. in rural areas in Bangladesh. Forest residues are mostly used for cooking purpose. Animal manures are usually used for rural cooking in the form of dung cake and dung stick and mostly for fertilizer. Bangladesh had 90.21 million tons recoverable biomass in 2012–2013 equivalent to 45.91 million tons coal equivalent as shown in Table 17 is comparable to some Asian countries. Table 18 shows the biomass potential of some Asian countries. The estimated sustainable non-plantation bioenergy potential in 2010 in China, India, Philippines, Sri Lanka and Thailand is about 8.90, 8.77, 0.97, 0.14 and 0.82 EJ respectively [75]. On the other hand, total amount of recoverable biomass was 74.128 million tons in 2003 equivalent to 38.41 million tons coal equivalent [7] as shown in Fig. 7. Therefore, Fig. 7 shows the increasing trend of biomass potential in Bangladesh.

Although Bangladesh has a huge potential of biomass from different sources, however, total recoverable amount are not available for electricity generation. All the agricultural field residues are used for fertilizer. On the contrary, animal dung is used as cooking fuel and fertilizer in Bangladesh. About 50% of rice husk is used for rural cooking and parboiling steam generation [47]. Some other process residues are used for cooking and animal feed. Forest residues are also used for the same purposes. It has been found that only 57% of poultry droppings are viable for small-scale power generation [78]. Therefore, MSW, bagasse, poultry droppings and 50% rice husk can be effectively used for electricity generation. Fig. 8 shows that forest residues and animal dung contribute the dominating portion of biomass potential in 2012–2013.

4. Technologies and organizations related to biomass in Bangladesh

Traditional use of biomass in cooking purpose in rural areas of Bangladesh causes adverse effects on environment. Biomass

Table 18
Biomass assessment of some Asian countries.

Country	Energy potential		Electricity generation (TWh)	Coal equivalent (million ton)
	Peta Joule	Reference (PJ)		
Bangladesh	1344.99	–	373.71	45.91
India	8764.00	[74]	2435.08	299.11
Sri Lanka	141.80	[75]	39.40	4.84
China	8899.80	[76]	2472.81	303.75
Thailand	821.40	[77]	228.23	28.03
Philippine	968.70	[28]	269.15	33.06

Table 17

Total biomass assessment in Bangladesh in 2012–2013.

Biomass sources	Biomass generation (million tons)	Dry biomass recovery (million tons)	Energy content (PJ)	Electricity generation (TWh)	Coal equivalent (million ton)	Gas equivalent (BCM)
Agricultural residues	94.10	36.48	582.33	161.80	19.88	14.72
Forest residues	17.44	14.32	210.64	58.53	7.19	5.33
Livestock residues	88.89	34.26	456.41	126.81	15.58	11.54
MSW	13.38	5.15	95.61	26.57	3.26	2.42
Total	213.81	90.21	1344.99	373.71	45.91	34.01

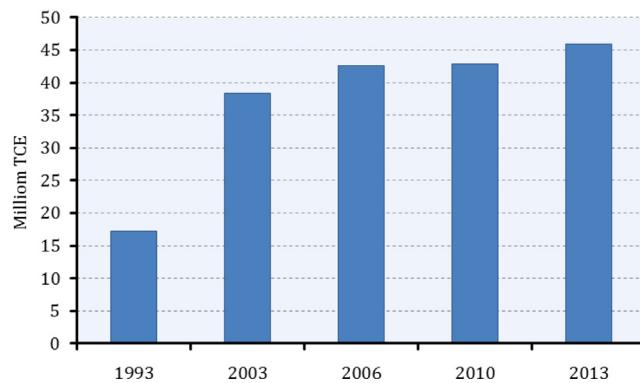


Fig. 7. Biomass energy potential pattern in Bangladesh.

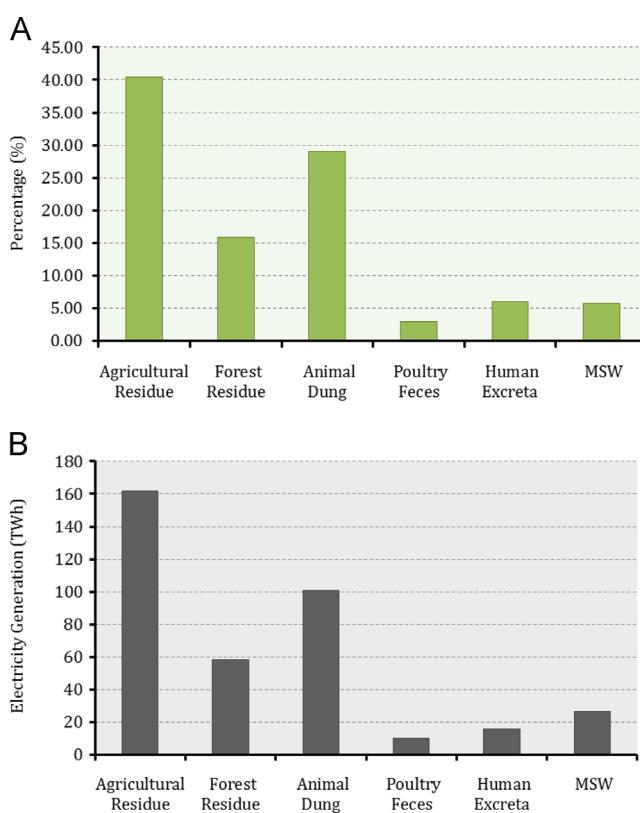


Fig. 8. Contribution of various biomass sources in Bangladesh according to (A) mass percentage (B) electricity generation.

burning is a significant source of greenhouse gas and particulate matter emissions to the troposphere such as carbon dioxide, methane and nitrous oxide. Moreover, kerosene and LPG actually produce fewer greenhouse gas emissions per unit of energy service than biomass fuels used in traditional ways. Table 19 shows the CO₂ emission from traditional burning of various fuels [79].

Thus, attention has been revived to the RETs for promoting sustainable development in rural areas of developing countries. Basically, their involvement provides the following benefits.

- Clean fuels for cooking and other basic household amenities.
- Liquid fuels and electricity to electrify the rural areas and to mechanize agriculture.
- Sufficiently low cost electricity to attract industrial activity to rural areas.
- Income source for unemployed rural people.
- Clean environment to enhance the health of rural people.

- Facility for night education for rural poor people.
- Facility for better health treatment, entertainment and other social activities in rural areas.

4.1. Improved cooking stoves (ICS)

About 90% of all families in Bangladesh use traditional mud made stove for their cooking and heating purposes. Nearly, 30 million households out of 32 million use this traditional stove for biomass burning. The overall efficiency of these traditional stoves is very low and only between 5% and 10% [80]. Table 20 shows the efficiencies of typical household stoves used in Asia [81]. The traditional stoves have been found to be highly inefficient and to emit copious quantities of smoke due to the incomplete combustion of biomass fuels. This inefficiency also has consequences on the environment.

It is well-thought-out that biomass burning is the main contributor of indoor air pollution. Women and children are the main victims from this pollution. About 2 million people a year die prematurely from illness attributable to indoor air pollution. Among these deaths, 44% are due to pneumonia, 54% from chronic obstructive pulmonary disease and 2% from lung cancer [82]. In Bangladesh, it has been estimated that 46,000 women and children die each year as a direct result of exposure to indoor air pollution while, 70% of the victims of indoor air pollution are children under five [83].

Therefore, emphasis has been given to develop improved cooking stove since more than 30 years by the Institute of Fuel Research and Development (IFRD) of the Bangladesh Council of Scientific and Industrial Research (BCSIR) to reduce the adverse effect. Recently, about 0.4 million domestic stoves and over 3000 commercial stoves have disseminated throughout the country under Sustainable Energy for Development (SED) program supported by the Bangladesh Ministry of Power, Energy and Mineral Resources which save at least 0.4 million tons of firewood a year [83]. It has been estimated that, Bangladesh has total 29 million ICS market potential. The specific benefits of the ICS are listed below.

- Reduction in cooking stove users' health hazards by decreasing indoor air pollution.
- Protection of the climate by reducing CO₂ emissions.
- Reduction in families' fuel expenses.
- Increase in combustion efficiency.

Table 19
Emission from various fuels [79].

Fuels	CO ₂ emission (kg/kg fuel)
Rice husk	1.49
Bituminous coal	2.46
Natural gas	1.93

Table 20
Efficiencies of typical household stoves in South Asia [81].

Fuel	Combustion efficiency (%)	Overall efficiency (%)
Biogas	99	57
LPG	98	54
Kerosene	98	50
Fuel wood	90	23
Crop residues	85	14
Dung	85	11

IFRD have developed a number of improved stoves. These have been categorized as follows [80]:

- Stoves without chimney which save 50–55% fuel compared to traditional stoves.
- Stoves with chimney which save 60–65% fuel.
- Stoves which have waste heat recovery system.

It has found that about 129 million stoves were installed by early 1992 in China where about 35.2 million stoves were installed in India by March 2003 [49]. Recently, Bangladesh has more than 400 promoters and 3000 sanitary shops to produce ICS [84].

4.2. Biogas plant

Biogas, a clean-burning methane-rich gaseous fuel produced through decomposition of biomass mainly animal manure and human excreta with absence of air. Biogas includes 40–70% methane (CH_4), 30–60% carbon dioxide (CO_2), 1–5% other gases by volume [85] and varying quantities of water (H_2O) with several trace gases like hydrogen sulfide (H_2S), nitrogen (N_2), ammonia (NH_3) and carbon monoxide (CO) [86]. Bangladesh is an agro-based country with a huge potential of biomass and has a temperature between 6 °C and 40 °C which is ideal for utilizing biogas technology. It has been estimated that 1 kg cattle dung can produce about 40 l of biogas; 1 kg of chicken droppings can produce about 70 l of biogas whereas 1 kg human excreta can produce 50 l of biogas [87]. The energy available from biogas is about 6 kWh/m³ which corresponds to half a liter of diesel oil and 5.5 kg of firewood [87]. Another study shows that 1 kg cattle dung can produce 0.037 m³ of biogas [49]. The density of biogas at standard temperature and pressure (STP) is considered about 1.15 kg/m³. Accordingly, available animal dung in 2012–2013 can produce 2.91 billion m³ of biogas in which only cow dung contributes 2.54 billion m³ of biogas. Therefore, biogas from animal dung is equivalent to 1.49 million tons of kerosene or 2.98 million tons of coal or 16.005 million tons firewood or 1.455 billion l of diesel. Furthermore, the poultry feces can generate 0.749 billion m³ of biogas. Every family of Bangladesh can use biogas plant as only human excreta produce 0.269 billion m³ of biogas equivalents to 1.48 million tons firewood. Besides, agricultural residues and MSW can be effectively utilized to produce subsequent amount of biogas.

Biogas is a clean and cheap fuel that can be used for both heating and lighting. In developing countries, biogas produced from domestic-scale digesters is used for cooking and to a smaller extent for water heating and lighting. The light power of a lamp consuming about 0.23 m³ of biogas per hour is equivalent to a 40 W light bulb [88]. Besides, by transferring biogas into electricity it can be used to run refrigerators, water heaters, television, power engines etc. Increasing trend of kerosene, diesel, LPG and other

conventional energy price made biogas more attractive for rural households and considered as a modern cooking fuel to reduce the health risks and time-loss suffered by women and children during cooking. Cost and characteristics of some modern fuel in Bangladesh are shown in Table 21.

Cooking and lighting with kerosene produce dangerous exposure to air pollutants for women and young children who spend much of their time indoors and directly related to cooking. However, biogas plants can be used as a replacement of fuel wood which makes cooking easier, cleaner and safer. It has been found that biogas contributes to the protection of the environment as about 4.7 t of carbon dioxide emissions can be saved by an average small-scale biogas plant per year [89].

A number of developing countries especially China and India have started biogas plant program. China has initiated this program first in 1973 and targeted to establish 7 million household-scale digesters during the year 1973–1978. However, the target failed due to quality control and management problems. In China about 5 million domestic plants were operating satisfactorily by 1994. In India almost 2.8 million domestic plants were installed by the end of 1998. According to India's Ministry of Non-Conventional Energy Sources, India has a potential of 12 million biogas digesters. However in 2011, India had the largest numbers of domestic digesters in the world with 4.4 million domestic biogas digesters. A national program had been started by the Netherlands Development Corporation to set up 36,450 biogas plants by 2009. Recently, GTZ in collaboration with BCAS has completed a feasibility study to encourage commercial poultry-based biogas plants [49]. In Bangladesh the first biogas plant for demonstration was established in 1972 at the Bangladesh Agricultural University (BAU), Mymensingh. According to IFRD, Bangladesh has a potential of about four million biogas plants. However, Bangladesh has only about 65,317 biogas plants with an efficiency of 85% as shown in Table 22. The study shows that:

- Over 65,317 fixed dome biogas plants have been installed in Bangladesh,
- Biogas plant, a clean technology removes bad smell emitting from poultry farms.
- Slurry, the by-product produced from the technology is used as fertilizer and fish feed.
- Biogas is sold at the rate of 300 BDT per connection.
- The technology is not disseminated according to desire yet due to lack of proper motivation, appropriate technology, rising cost of plant.
- Biogas plants can be set up at any households in which 30 kg of cow dung or poultry feces are available every day.

Recently, Bangladesh has about 215,000 poultry farms and 15,000 cattle farms which may be an excellent source for electricity generation by establishing biogas plants. The poultry farms

Table 21
Costs and physiognomies of common fuels in Bangladesh.

Fuel	Capital cost (BDT)	Fuel cost (BDT/l)	Remarks
Biogas	30000–35000	0	Formed by anaerobic decomposition of dung or leafy biomass material; commercially available with no direct fuel cost; economical and important option for rural areas in Bangladesh like other parts of Asia
Kerosene	400–1200	68	Commercially available in liquid or gaseous form; easy to transport, distribute and purchase; produce more emissions and hazard effects on environment with a higher risk of injury than LPG
LPG	4500–5800 ^a	56 ^b	Commercially available in urban areas than rural areas; low-income households in rural areas of Bangladesh are unable to use due to large start-up cost and refill cost

^a Includes the LPG cylinder price.

^b Price is taken in BDT/kg.

are considered as the second largest source of grameen employment. It is estimated that about 2000 MW of electricity can be generated from this huge potential of poultry feces in the country.

4.3. Biomass briquetting

Biomass briquette is a solid compact of different sizes produced by application of pressure from loose biomass includes agricultural residues, residues from wood industry etc. Biomass briquette has the following advantages [90–94]:

- Higher calorific value per unit volume than traditional biomass.
- Ease of transportation, storage and residual disposal.
- Provide uniform shape.
- Reduce indoor air pollution.

Briquetting is an ancient concept which was first introduced in 1864 in USA. Recently, biomass briquetting is considered as an established technology in a number of Asian countries like Japan, Korea, Taiwan, China, India, Thailand, Bangladesh and Malaysia. It has been found that about 600 briquetting machines are operating in China. However, Malaysia has the biggest briquetting plant [49]. Bangladesh has started the activities of biomass briquetting in early 1980s. The technology originally developed by local entrepreneurs without any support from the government or donor agencies. Later, KUET (formerly BIT, Khulna) and BRRI developed this technology. Recently, briquettes made from rice husk by BRRI gave 20% better efficiency. A study shows that, the production cost of briquette is BDT 1.75 kg⁻¹ [95].

Among the two types of briquetting machines (piston press and screw extruders), screw extruder technology has become successful in briquetting rice husk and saw dust in Europe, Japan, Malaysia, Taiwan and Thailand [96]. In Bangladesh, heated-die-type machines are operating. The country has a tremendous potential of raw materials to utilize briquetting. It is estimated that, at present only about 1000 machines are operating in the country although the huge bio-residues are sufficient to run more than 18,000 briquetting machines [92]. Table 23 shows the briquetting machines in some greater districts in Bangladesh. Biomass briquettes are becoming popular in Bangladesh and using in tea stalls, restaurants and student housings for better combustion characteristic. A recent survey shows that the briquette price is 60–70% more than wood in some district like Gaibanda and Sirajgonj.

4.4. Gasification and pyrolysis of organic solid wastes

Pyrolysis, a thermochemical decomposition of organic materials in the absence of oxygen under pressure operating at a temperature above 430 °C is not well known in Bangladesh yet [98]. First biomass gasification was carried out in blast furnaces over 180 years ago. Recently, gasification is an established biomass technology in some Asian countries like India, China etc. In India,

about 17,000 power gasifiers of capacity 24 MW were installed during the year 1995–1996. On the other hand, about 800 gasifiers were installed in China [49]. However, Bangladesh is still new in the field of biomass gasification.

The first commercial biomass gasification plant of capacity 250 kW has been established by IDCOL at Kapasia, Gazipur in Bangladesh. Total cost of this project was BDT 25 million. Another rice husk gasification plant of capacity 200 kW has been set up by LGED at Dinajpur. Recently, IDCOL is financing a 400 kW rice husk gasification plant along with a precipitated silica plant at Chilarong, Thakurgaon sadar, Thakurgaon. Total cost of this project is BDT 64.25 million [99].

On the contrary, Rajshahi University of Engineering and Technology (RUET), Bangladesh has been carrying out some research on production of alternative liquid fuel from organic solid wastes through pyrolysis since 2000. Recently, liquid fuel has been produced from waste scrap tire. A horizontal axis rotary type pyrolysis plant comprises of two units each of capacity 9 t/day has been installed by "Radiant Renewable Energy Ltd." at Kainzanul, Vawal Mirjapur, Gazipur, Bangladesh. The reactor is heated externally by burning pyro-oil (initially) and then pyro-gases and the products are heavy and light liquids, char and scrap steels. The maximum liquid production rate is 45 wt% of waste tire feeds. The yield from pyrolysis process is called bio-oil.

Bangladesh has abundant algae potential and hilly areas to cultivate *Jatropha curcas*. It is estimated that approximately 3000 l of oil can be obtained per hectare of land. Therefore, considerable amount of bio-oil can be harvested through pyrolysis. However, no initiatives have been taken for commercial production of bio-oil yet. Currently, only BAU is conducting research work on *Jatropha curcas*. Biofuel or biodiesel is clean burning oil produced by transesterification of bio-oil with short chain alcohols. Table 24 shows biodiesel production from common oil crops [100]. A recent study shows the effective use of bio-oil in cooking purpose [101]. On the contrary, this biodiesel can be used in vehicles and power plants to generate electricity.

4.5. Municipal solid waste (MSW) composting plant

Bangladesh is environmental threaten country producing huge amount MSW. This huge amount of MSW creates hazardous

Table 23
Briquetting machines in some greater districts in Bangladesh.

Greater district	Number of machines	Reference	Number of foreign machine
Sylhet	248	[97]	15
Khulna	174	[49]	2
Chittagong	135	[49]	–
Rajshahi	268	[49]	–
Barisal	32	[49]	–
Dhaka	47	[49]	–
Total	904	–	17

Table 22

Summary of biogas plant installation by different organization in Bangladesh.

Organizations	Type of systems installation	Number	Capacity (cft/day)
IDCOL's partner organization	Domestic biogas plant	26311	42–170
IFRD of BCSIR	Phase-I; phase-II	22334	100–200; 120–420
GS	Family biogas plant	7000	120–420
BRAC	Family biogas plant; power generating unit	3664	120–420; Each of 800 WP
LGED	Family biogas plant; community biogas plant	3000	120–420; Up to 2000
Others	Family biogas plant	3008	120–420
Total	–	65317	

effects on the environment and human being. Composting, a natural recycling process which breaks down the organic matter may be an effective way to manage the generated MSW. Therefore, community based waste management and composting pilot program: urban slum and suburb project has been started by Government of Bangladesh along with UNICEF.

Bangladesh has three waste concern's clean development (CDM) based compost plant at Bulta, Roopganj and greater Dhaka. Among the three plants, Bulta is the first compost plant initiated construction on 25 November 2008. The plant has a 130 t-per-day capacity with 130 workers. On November 24, 2011 a team of government high officials visited waste concern's joint venture compost plant located at Bulta, Roopganj, and greater Dhaka [102]. Recently, PRISM has started to compost the collected organic part of solid wastes in four compost plants in suitable places in Khulna City Corporation under community based urban wastewater treatment project financed by UNDP [103].

5. Research and development (R&D) activities related to biomass

Recently, several governmental, nongovernmental organizations and technical universities have taken some initiatives to develop biomass technologies like biogas plants, ICS, pyrolysis technology, composting plant etc. Among them IDCOL, GS, BCSIR, IGED, BRAC, RSF are currently engaged in dissemination of domestic biogas plants and ICS in Bangladesh. Table 25 shows the R&D activities of various organizations in Bangladesh.

5.1. Infrastructure development company limited (IDCOL)

IDCOL, a government organization established on 14 May 1997 is playing the significant role for dissemination of biogas plants in Bangladesh. In 2006, IDCOL has started the program to establish domestic biogas plant with 30 partner organizations. Up to December 31, 2012 IDCOL have so far constructed total of 26311 biogas plants all over the country under National Domestic Biogas and Manure Program (NDBMP) with support from GOB, SNV-

Table 24
Averages biodiesel production from common oil crops [100].

Plant	lb. oil/acre	Gallons of biodiesel/acre
Algae	6757	700
Coconut	2070	285
Jatropha	1460	201
Rapeseed	915	126
Peanut	715	112
Sunflower	720	99
Soybean	415	62

Table 25
Status of R&D activities of different organizations [49].

Technology	Related organizations	Activities
Improved cooking stoves	IFRD of BCSIR, GS, BRAC, RSF, VERC, GIZ, UNDF	Three basic types (Without chimney, with chimney, and with waste heat utilization) of stove have been developed at IFRD. However, VERC disseminates 7 models of ICS
Briquetting machine	KUET, BRRI	KUET has developed better machines with longer screw life under the 'RETs in Asia' program
Biogas plant	IFRD of BCSIR, IGED, GS, BAU, BRAC, IDCOL, RSF	Fixed-dome type plants are indigenously designed, constructed and disseminated with government subsidy of BDT 5000 where IDCOL donates BDT 9000 for each plant to its POs
Pyrolysis technology	RUET, Radiant Renewable Energy Ltd.	Rajshahi University of Engineering and Technology (RUET) is conducting research and development works for pyrolysis to produce of alternative liquid fuel since 2000. Radiant Renewable Energy Ltd. has started to produce liquid fuel from scrap tire

Netherlands development organization and Kfw. All the biogas plants are fixed dome type with gas production capacities of 1.2, 1.6, 2.0, 2.4, 3.2 and 4.8 m³ per day. IDCOL provides BDT 9000 per plant as investment subsidies to the biogas households. Therefore, IDCOL have set a target to establish one lakh biogas plants by 2016. Furthermore, IDCOL is financing to set up of three biogas based electricity generation plants, one in Mymensingh and two in Gazipur and one organic fertilizer plant in Gazipur by Paragon Agro Ltd. Total project cost is BDT 149.40 million. Paragon Poultry Ltd. will buy the electricity generated from these plants at a price BDT 4 kWh⁻¹; on the other hand fertilizer will be sold in the market at a price of BDT 15 per 1 kg packet and BDT 400 per 40 kg packet [104].

5.2. Grameen shakti (GS)

Grameen shakti is a private company established in 1996 which has 46 grameen centers with 130 engineers working in 50,000 villages for their renewable energy program. GS has started its biogas program in 2005. Although GS is working as partner organization, they have their own biogas program. They have so far constructed about 23,911 biogas plants as partner organization under IDCOL's program and their own program. They have constructed around 7000 biogas plants in the country under their own program and providing technical and financial support for the generation of electricity using biogas.

Besides, GS has started their improved cooking stoves (ICS) program in 2006. So far GS has successfully installed about 583,982 ICS throughout the country. GS aims to establish about 250,000 biogas plant and 5,000,000 ICS by the year 2015.

5.3. Bangladesh council of scientific and industrial research (BCSIR)

BCSIR, a government research organization is pursuing various researches on renewable energy technology. BCSIR has started its biomass research in 1973. The concept of ICS was patented by IFRD of BCSIR in 1978 and developed three basic types of stove. However, IFRD was established as a separate institute of BCSIR in 1980. Recent survey shows that, BCSIR has disseminated about 300,000 ICS in phases I and II also phase III will distribute 28,000 stoves in seven districts.

IFRD has also biogas program and started a biogas dissemination project called "Mitigation of carbon emission and extension of alternative energy usage through dissemination of biogas plant and improved cook stove" funded by climate change trust fund under ministry of environment and forest. IFRD has been engaged in the installation of 22,334 domestic biogas plants. Moreover, IFRD has taken up a project for setting up 2800 new domestic biogas plants in seven districts by seven agencies.

5.4. Bangladesh rural advancement committee (BRAC)

BRAC is another ancient non-government organization established as a relief organization in 1972 after liberation war [105]. However, BRAC is pursuing the renewable energy activities. BRAC is implementing biogas project as experimental basis since September 1996. Recently, the organization has disseminated about 3664 biogas plant of capacity 120–420 ft³/day. The organization is also working as a partner organization with IDCOL in ICS program. BRAC has a future plan to install 50,000 biogas plants in the country [49].

5.5. Local government engineering department (LGED)

LGED is a government organization playing a vital role in rural infrastructure development in the country and providing technical support to the local government institutions. They have over 500 offices at the district and sub district levels throughout the country. Nevertheless, LGED has involvement in some renewable energy program. LGED has installed a 4 kW power generation plant that can use the biogas generated from poultry droppings at Faridpur Muslim Mission School, an orphanage for 500 students, is located 60 mile southwest of Dhaka city [104]. LGED has also installed a 4 kW electricity generation unit that runs on biogas generated from poultry droppings. The project was completed in 2002. Recently, about 3000 biogas plant has been established by LGED.

5.6. Rural service foundation (RSF)

RSF has entered into the energy saving sector i.e. ICS program with the cooperation of GTZ to reduce the indoor air pollution and to improve the kitchen environment. So far RSF has constructed 4850 ICS till November, 2012. Besides, RSF is working as constructor partner organization of IDCOL from 2006. Recent survey shows that, RSF has installed 1164 biogas plants till November, 2012 with IDCOL partnership. Furthermore, RSF has signed an agreement with GTZ to implement the biogas plant construction [106].

5.7. Village education resource center (VERC)

VERC is a local non-government organization that has been working on ICS program since 1987. Later, it has formed a national network named "Improved cook stoves program in Bangladesh" in the year of 2000 with the support of ARECOP-Indonesia. Through the network, approximately 42,000 ICS are installed. About 20 demonstration centers and 864 staff and community people are working on ICS technologies. Recently, VERC is implementing a project entitled "Development of an improved cook stoves project to secure carbon finance for its long term sustainability" since June 2008 covering five sub-districts in Rajshahi division, three sub-districts in Rangpur division and one sub-district under Dhaka division of Bangladesh. It has been estimated that, about 6292 ICS are disseminated under this project [107]. VERC has made a future plan to disseminate 114,000 ICS in 13 districts by 2015 for 592,800 peoples.

5.8. GIZ (German agency for international cooperation) Bangladesh

GIZ Bangladesh is another local non-government organization working to raise awareness on improved cook stoves and biogas through GIZ support. GIZ has supported 200 partner organizations as primary players in promoting improved stoves throughout Bangladesh. The network has been working over 7 years and reaching sales of 45,000 ICS. It is now expanding its partnership to sanitary shops and masons [108].

5.9. United Nations Development Program (UNDP)

UNDP embarked on its journey in Bangladesh on 31 July 1972. UNDP is involved with various governmental organizations to thrive towards economic and social development in Bangladesh [109]. They have focused on providing ICS to the ultra-poor populations which are most vulnerable to natural disasters such as cyclones and floods. The stoves are around 90% subsidized and users only pay around BDT 90. Recently, it has established about 40,000 ICS however aims to expand this quantity to 400,000.

6. Concluding remarks

Biomass is considered as a main energy source in rural areas in Bangladesh. Biomass energy potential in Bangladesh has been estimated. The current estimation specifies that in 2012–2013, the total annual biomass generation and dry recoverable rates in Bangladesh were 213.81 and 90.21 million tons respectively. Agricultural residues remain the dominated in dry biomass potential as of 40.44% followed by cow dung 25.39%. The recoverable biomass potential in 2012–2013 is equivalent to 373.71 TWh. Therefore, this huge biomass can be used for decentralized electricity generation in rural areas in the country. However, electricity generation from biomass is not well established in Bangladesh yet. On the other hand, the US has generated about 56.7 TWh of electricity from solid biomass in 2011.

During the last two decades, a numerous research activities have been pursuing on RETs by some governmental, non-governmental organizations and technical universities in Bangladesh to improve the biomass utilization pattern. Recently, some RETs like ICS and biogas plant are well established in the country. IDCOL, BCSIR, LGED with some other NGOs like GS, BRAC and VERC have taken several programs to develop and disseminate ICS and biogas plant throughout the country, although still there are lots of barriers. Consequently, GOB should give emphasis on the development of RETs to remove this barrier as these programs will be effective to eliminate rural unemployment and electricity problem. In conclusion, small-to-medium-scale biomass-based electricity generation plant can be established for supplying electricity to rural and remote areas in Bangladesh.

Reference

- [1] Nasir NF, Daud WRW, Kamarudin SK, Yaakob Z. Process system engineering in biodiesel production: a review. *Renew Sustainable Energy Rev* 2013;22:631–9.
- [2] British Petroleum (BP). BP Statistical Review of World Energy, British: BP Plc, 2013. (<http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy-2013.html>) [accessed October 2013].
- [3] Bhattacharya SC, Arul Joe M, Kandhekar Z, Abdul Salam P, Shrestha RM. Greenhouse-gas emission mitigation from the use of agricultural residues: the case of rice husk. *Energy* 1999;24(1):43–59.
- [4] Demirbas A. Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy Convers Manag* 2001;42:1357–78.
- [5] Susta Miro R, Luby P, Mat SB. Biomass energy utilization and environment protection commercial reality and outlook. (http://www.energy.siemens.com/mx/pool/hq/energytopics/pdfs/en/industrial%20applications/4_Biomass_Energy.pdf).
- [6] Cai JM, Liu RH, Deng CJ. An assessment of biomass resources availability in Shanghai: 2005 analysis. *Renew Sustainable Energy Rev* 2008;12:1997–2004.
- [7] Hossain AK, Badr O. Prospects of renewable energy utilization for electricity generation in Bangladesh. *Renew Sustainable Energy Rev* 2007;11:1617–49.
- [8] Bildirici Melike E. Economic growth and biomass energy. *Biomass Bioenergy* 2012.
- [9] Yemane Wolde R. Energy demand and economic growth: the African experience. *J Policy Model* 2005;27:891–903.
- [10] Toman T, Jemelkova B. Energy and economic development: an assessment of the state of knowledge. *Energy J* 2009;24:93–112.
- [11] REN21. Global status report 2013. (http://www.ren21.net/portals/0/documents/resources/gsr/2013/gsr2013_lowres.pdf).

[12] Current status of renewable energy across the globe & Bangladesh. (<http://ebiozone.com/current-status-of-renewable-energy-across-the-globe-bangladesh/>) [accessed May 2013].

[13] Bangladesh Bureau of Statistics (BBS). Statistical Year Book of Bangladesh, Agricultural Year Book of Bangladesh. (<http://www.bbs.gov.bd/home.aspx>) [accessed January 2014].

[14] Food and Agriculture Organization of the United Nations (FAO). (<http://www.fao.org/countryprofiles/index/en/?iso3=BCD>) [accessed May 2013].

[15] (<http://www.mapsofworld.com/bangladesh/bangladesh-political-map.html>) [accessed on May 2013].

[16] The World Bank. (<http://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE>) [accessed January 2014].

[17] Bangladesh Power Development Board (BPDB). (<http://www.bpdb.gov.bd/bpdb/>) [accessed January 2014].

[18] Gas expansion power plants with modular system gas expanders. A publication of Spilling Energy System, 2008; vol. 27: p. 262–5.

[19] Ravindranath NH, Hall DO. *Biomass, energy, and environment: a developing country perspective from India*. Oxford: Oxford University Press; 1995.

[20] Rashid MA. A review of the forest status in Bangladesh and the potential for forest restoration for wildlife conservation.

[21] Bangladesh Sugarcane Research Institute. Ministry of Agriculture, Government of the People's Republic of Bangladesh, (<http://www.bsri.gov.bd/>) [accessed January 2014].

[22] Department of Agricultural Extension. Government of the People's Republic of Bangladesh. (<http://www.dae.gov.bd/>) [accessed January 2014].

[23] Bangladesh Agriculture – products. (<http://www.indexmundi.com/agriculture/?country=bd>) [accessed January 2014].

[24] Cotton Development Board (CDB). Government of the People's Republic of Bangladesh. (<http://www.cdb.gov.bd/>) [accessed January 2014].

[25] Apex planet. (<http://apexplanet.blogspot.com/2012/11/lakkatura-tea-esta-te-oldest-tea-garden.html>) [accessed January 2014].

[26] Cotton Development Board (CDB). Government of the People's Republic of Bangladesh. (<http://www.cdb.gov.bd/>) [accessed January 2014].

[27] Ministry of Finance. Government of the People's Republic of Bangladesh. (<http://www.mof.gov.bd/en/>) [accessed January 2014].

[28] Elauria JC, Castro MLY, Elauria MM, Bhattacharya SC, Abdul Salam P. Assessment of sustainable energy potential of non-plantation biomass resources in the Philippines. *Biomass Bioenergy* 2005;29(3):191–8.

[29] Bhattacharya SC, Shrestha RM, Ngamkajurnvivat S. Potential of biomass residue availability: the case of Thailand. *Energy Sour* 1989;11(3):201–16.

[30] Bhattacharya SC, Pham HL, Shrestha RM, Vu QV. CO₂ emissions due to fossil and traditional fuels, residues and wastes in Asia. AIT Workshop on Global Warming Issues in Asia, AIT, Bangkok, Thailand, 8–10 September 1992.

[31] Ramachandra TV, Subramanian DK, Joshi NV, Gunaga SV, Haritanra RB. Domestic energy consumption patterns in Uttara Kannada District, Karnataka State, India. *Energy Conserv Manag* 2000;41:775–831.

[32] Desai AV. Patterns of energy use in developing countries. Tokyo, Japan: UNU; 1990.

[33] Ishaque M, Chahal DS. Crop residues. In: Food, Feed and Fuel from Biomass. Chahal DS, editor, 1991; p. 15.

[34] BEPP. Bangladesh Energy Planning Project: Draft Final Report, Rural Energy and Biomass Supply, 1985; vol. IV.

[35] Strehler, A., Stutzle, W. Biomass Residues, In: Biomass Regenerable Energy. Hall DO, Overend RP, editors, 1987.

[36] Vimal OP. Residue utilization, management of agricultural and agro-industrial residues of selected tropical crops (Indian experience). In: Proceedings of UNEP/ESCAP/FAO Workshop on Agricultural and Agro-industrial Residue Utilization in Asia and Pacific Region, 1979.

[37] USAID. Baling Sugarcane Tops and Leaves: The Thai Experience, 1989.

[38] Ryan P, Openshaw K. *Assessment of biomass energy resources: a discussion on its needs and methodology*, Industry and Energy Department working paper. Energy series paper; No. 48. Washington, DC: World Bank; 1991.

[39] Smill V. Biomass Energies, Resources, Links and Constraints, 1983.

[40] Barnard G, Kristoferson L. *Agricultural residues as fuel in the third world*. Energy Information Program, Earthscan, Technical Report No. 4. London: Earthscan – The Beijer Institute; 1985.

[41] Kristoferson LA, Bokalders V. *Renewable energy technologies: their application in developing countries*. London: IT Publications; 1991.

[42] Black, Veatch (Thailand). Thailand biomass-based power generation and cogeneration. In: Small rural industries (Progress report), January 1999.

[43] Bhushan B. Agricultural residues and their utilization in some countries of South and South-East Asia. In: Residue Utilization: Management of Agricultural and Agro-industrial Residues, FAO/UNEP, 1977; vol. 1.

[44] Massaquoi JGM. Agricultural residues as energy source. In: Energy for Rural Development. Bhagvan MR, Kakekezi, S, editors, 1990.

[45] Webb B. Technical aspects of agricultural and agro-industrial residues utilization. In: Proceedings of UNEP/ESCAP/FAO Workshop on Agricultural and Agro-industrial Residue Utilization in Asia and Pacific Region, 1979.

[46] DEDP. Report on coconut residue investigation. Department of Energy Development and Promotion, Thailand, 1994.

[47] Mondal MAH, Denich M. *Assessment of renewable energy resources potential for electricity generation in Bangladesh*. Renew Sustainable Energy Rev 2010;14(8):2401–13.

[48] Biomass – SEPS. (<http://www.seps.sk/zp/fond/dieret/biomass.html>) [accessed May 2013].

[49] Islam MR, Islam MR, Beg MRA. Renewable energy resources and technologies practice in Bangladesh. *Renew Sustainable Energy Rev* 2008;12:299–343.

[50] Yokoyama S, Ogi T, Nalampoon A. Biomass energy potential in Thailand. *Biomass Bioenergy* 2000;18:405–10.

[51] Koopmans A. Biomass energy resources for power and energy. In: Options for dendro power in Asia: report of the expert consultation 1998. Manila, Philippines: FAO, 1–3 April 1998.

[52] Mondal AH. Implications of renewable energy technologies in the Bangladesh power sector: long-term planning strategies. ZEF, 2010.

[53] Koopmans A, Koppejan J. Agricultural and forest residues—generation, utilization and availability. In: Regional consultation on modern applications of biomass energy 1997. Kuala Lumpur, Malaysia: FAO, 6–10 January 1997.

[54] Demirbaş Ahyan. *Calculation of higher heating values of biomass fuels*. Fuel 1997;76(5):431–4.

[55] Hashem MA. Wood fuel utilization in rural industries. In: National Training Course on Wood fuel in Bangladesh—Production and Marketing 1996, Bogra, Bangladesh: FAO, 7–11 December 1996.

[56] APPSOS II. *Biomass energy in the Asia-pacific region: current status, trends and future setting by Tini Gumartini*. Bangkok: Food and Agriculture Organization (FAO) of the United Nations regional office for Asia and the Pacific; 2009.

[57] Food and Agriculture Organization (FAO). Energy conservation in the mechanical forest industries. FAO Forestry paper No. 93, FAO-Rome, 1990.

[58] Food and Agriculture Organization (FAO). Year book of forest products, 2011. (<http://www.fao.org/docrep/018/i3252m/i3252m00.pdf>).

[59] Ministry of Finance (MoF). Government of the People's Republic of Bangladesh. (http://www.mof.gov.bd/en/budget/13_14/ber/bn/Chapter-07%20_Bangla%202013.pdf).

[60] Islam MN. Energy security issues of Bangladesh. *Bangladesh: Engineering News, Institute of Engineers*; 2000.

[61] Narang HP, Parashar DC, Bhattacharya SC, Salam PA. *A study of biomass as a source of energy in India*. RERIC Int Energy J 1999;21:11–23.

[62] Francisco Rosillo Callé. The Biomass Assessment Handbook: Bioenergy for a Sustainable Environment; 64 p. www.books.google.com.bd/books?isbn=1136554890.

[63] Othman MYH, Yatim B, Salleh MM. Chicken dung biogas power generating system in Malaysia. *Renew Energy* 1996;9:930–3.

[64] Parikh JK, Ramanathan R. Linkages among energy, agriculture and environment in rural India. *Energy Econ* 1999;21:561–85.

[65] Bhuiyan SH. A crisis in governance: urban solid waste management in Bangladesh. *Habitat Int* 2010;34(1):125–33.

[66] Parizeau K, Maclare V, Chanty L. Waste characterization as an element of waste management planning: lessons learned from a study in Siem Reap, Cambodia. *Resour Conserv Recycl* 2006;49:110–28.

[67] Smith C, Whitty K, Quintero M, Ojeda BS. Opportunities for Energy Production from Solid Waste in the Mexicali Region. Annual Meeting of the American Institute of Chemical Engineers. Salt Lake City: Utah, November 2–5, 2007.

[68] Country Analysis Paper (Draft) Bangladesh. Third Meeting of the Regional 3R Forum in Asia Technology. Singapore, 5–7 October 2011.

[69] Mukherjee D, Chakrabarti S. *Fundamentals of renewable energy systems*. 1st ed. Delhi, India: New Age International Publishers; 2007.

[70] Alamgir M, Ahsan A. Municipal solid waste and recovery potential: Bangladesh perspective. *Iran J Environ Health Sci Eng* 2007;4:67–76.

[71] Bose SK. Wood fuel production programs and strategies of the forest department. In: National training course on wood fuel in Bangladesh—Production and marketing 1996. Bogra, Bangladesh: FAO, 7–11 December 1991.

[72] Alam S. *Integrated modeling of a rural energy system: a system dynamics approach*. (Ph.D. thesis). Dhaka, Bangladesh: Department of Electrical and Electronics Engineering, Bangladesh University of Engineering and Technology; 1991.

[73] Biswas WK, Lucas NJD. Energy consumption in the domestic sector in a Bangladesh village. *Energy* 1997;22:771–6.

[74] Ravindranath NH, Somashekhar HI, Nagaraja MS, Sudha P, Sangeetha G, Bhattacharya SC, et al. Assessment of sustainable non-plantation biomass resources potential for energy in India. *Biomass Bioenergy* 2005;29(3):178–90.

[75] Bhattacharya SC, Abdul Salam P, Runqing H, Somashekhar HI, Racelis DA, Rathnasiri PG, et al. An assessment of the potential for non-plantation biomass resources in selected Asian countries for 2010. *Biomass Bioenergy* 2005;29(3):153–66.

[76] Junfeng L, Runqing H, Yanqin S, Jingli S, Bhattacharya SC, Abdul Salam P. Assessment of sustainable energy potential of non-plantation biomass resources in China. *Biomass Bioenergy* 2005;29(3):167–77.

[77] Sajjakulnukit B, Yingyuad R, Maneekhao V, Pongnarinatasut V, Bhattacharya SC, Abdul Salam P. Assessment of sustainable energy potential of non-plantation biomass resources in Thailand. *Biomass Bioenergy* 2005;29(3):214–24.

[78] Zaman SAU. The potential of electricity generation from poultry waste in Bangladesh: a case study of Gazipur district [Dissertation]. University of Flensburg, 2007.

[79] (http://www.pfpi.net/wp-content/uploads/2011/04/PFPI-biomass-carbon-accounting-overview_April.pdf) [accessed June 2013].

[80] Banu LB. Technologies for efficient use of wood fuel: improved chulli, compressed husk, briquetting and other technologies. In: National training

course on wood fuel in Bangladesh—production and marketing 1996. Bogra, Bangladesh: FAO, 7–11 December 1996.

[81] RWEDP and UNEP. Reducing greenhouse gas emissions by promoting biomass energy technology in South Asia. Thailand: FAO, 2000.

[82] World Health Organization (WHO). (http://www.who.int/mediacentre/fact_sheets/fs292/en/) [accessed June 2013].

[83] GIZ. Improved cooking stoves save lives. Sustainable Energy for Development. (http://www.cleancookstoves.org/resources_files/improved-cooking-stoves-save-lives.pdf) [accessed June 2013].

[84] Eric Otto Gomm. Improved Cook Stoves in Bangladesh – Challenges and Opportunities – regional intergovernmental consultation on near-term climate protection and clean air benefits in Asia and the pacific. Bangkok, 4–5 February 2013.

[85] Rehling U. Small biogas plants. Biogas plant for rural household. Design & Construction, SESAM Sustainable Energy Systems and Management, Flensburg, Germany, 2001. (<http://www.uni-flensburg.de/sesam/>) [accessed June 2013].

[86] Description of the biggest production in an agricultural biogas plant. (<http://www.bios-bioenergy.at/en/electricity-from-biomass/biogas.html>) [accessed June 2013].

[87] NWP, editor. Smart Sanitation Solutions. Examples of innovative, low-cost technologies for toilets, collection, transportation, treatment and use of sanitation products. Amsterdam: Netherlands Water Partnership (NWP), 2006. (<http://www.ircwash.org/sites/default/files/NWP-2006-Smartsanitation.pdf>) [accessed June 2013].

[88] ASHDEN, editor. Clean cooking and income generation from biogas plants in Karnataka. London: The Ashden Awards for Sustainable Energy, 2007. (http://www.ashden.org/finalists_2007) [accessed June 2013].

[89] ASHDEN, editor. Domestic biogas for cooking and sanitation. London: The Ashden Awards for Sustainable Energy, 2005. (<http://www.ashden.org/winners/bsp>) [accessed June 2013].

[90] Bhattacharya SC, Leon MA, Rahman MM. A study on improved biomass briquetting. In: Proceedings of the International Conference on Biomass-based Fuels and Cooking Systems, BFCS, Pune, India, 2000; p. 20–24.

[91] Bhattacharya SC, Leon MA, Rahman MM. A study on improved biomass briquetting. Energy Sustainable Dev 2002;2:106–10.

[92] Moral MNA. Biomass densification: development of briquetting packages in Bangladesh. UK: World Renewable Energy Congress (WREC); 2000.

[93] Moral MNA, Rahman MM. Utilization of biomass for briquetting in Bangladesh. In: Proceedings of the 4th International Conference on Mechanical Engineering, Dhaka, Bangladesh, 2001.

[94] Rahman ANMM, Moral MNA, Rahman MM. State of the art of biomass briquetting in Bangladesh. In: Proceedings of the International Conference and Workshop on Critical Issues in Energy and Development – Challenges for the OIC Countries, Dhaka, Bangladesh, 2000; p. 234–43.

[95] Ahmed S, Rahman MM, Islam MA, Mashud M, Moral MNA. Role of biomass briquetting in the renewable energy sector and poverty diminution for Bangladesh.

[96] Babu D, Yuvaraj N. Biomass densification—a solid (fuel) solution. TERI Newswire 2001, vol. 7. India: Energy and Resources Institute; 2001.

[97] Alam MM, Islam H, Hasan M, Siddique TA. A study of biomass briquette in Bangladesh.

[98] Mohan D. Pyrolysis of wood/biomass for bio-oil: a critical review. Energy Fuels 2006;20:848–89.

[99] Infrastructure Development Company Limited. (<http://www.idcol.org/energyProject.php>) [accessed June 2013].

[100] Sazdanoff Nicholas. Modeling and simulation of the algae to biodiesel fuel cycle, 2006.

[101] Halder PK, Joardder MUH, Beg MRA, Paul N, Ullah I. Utilization of bio-oil for cooking and lighting. Adv Mech Eng 2012; 2012, 5 pages (Article ID 190518), <http://dx.doi.org/10.1155/2012/190518>.

[102] Waste Concern. (<http://www.wasteconcern.org/index.php>) [accessed June 2013].

[103] PRISM Bangladesh. (<http://www.prismbd.org/projects2.htm>) [accessed June 2013].

[104] Special issue – Africa: improving modern energy services for the poor. In: Karekezi S, Tefera M, Mapako M, editors. Energy Policy, 30. Oxford: Elsevier Science Ltd.; 2002.

[105] Bangladesh Rural Advancement Committee (BRAC). (<http://www.brac.net/>) [accessed June 2013].

[106] Rural Service Foundation (RSF). (<http://www.rsf-bd.org/program.htm>) [accessed June 2013].

[107] Village Education Resource Center (VERC). (<http://www.verc.org/ics.html>) [accessed June 2013].

[108] United States Agency for International Development. Assessment of the Improved Stove Market in Bangladesh, January 2012.

[109] United Nations Development Program (UNDP). (<http://www.undp.org.bd/>) [accessed June 2013].